AC Loss Studies in HTS Conductors

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- $100k BNL
- $150k LANL

Outline of Presentation

1st Generation: BSCCO

    Cable 2 phase losses: Background   Steve

    Losses in loops

2nd Generation: YBCO

    AC Losses in 'nearly' perfect films   Mas
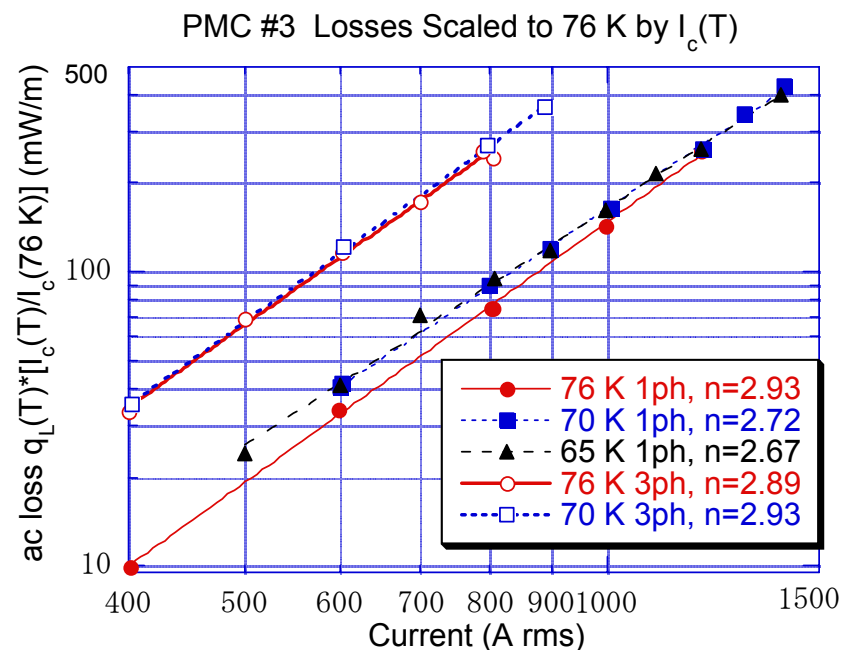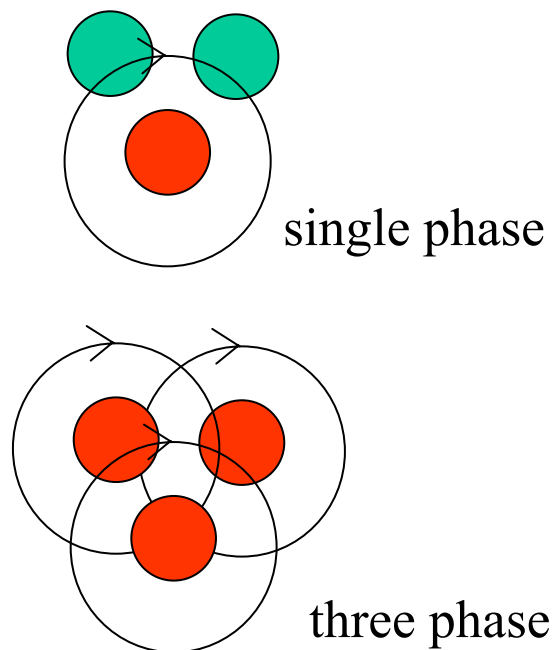
    Coated conductor measurements   Steve
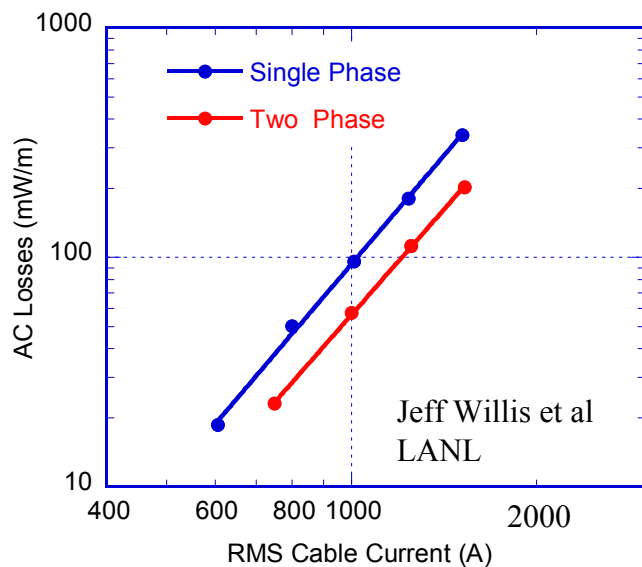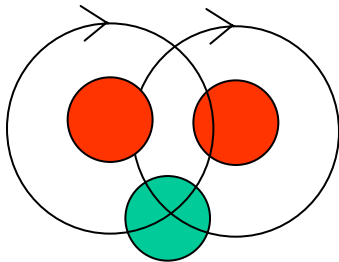
Plans, Integration etc

ac losses in BSCCO cables

Measurements on losses on 1m cable sections at LANL have previously shown significant (two to three times) increases in loss in 3 phase configuration over single phase.

single phase

three phase

PMC #3 Losses Scaled to 76 K by $I_c(T)$

Legend:
- 76 K 1ph, n=2.93
- 70 K 1ph, n=2.72
- 65 K 1ph, n=2.67
- 76 K 3ph, n=2.89
- 70 K 3ph, n=2.93

y-axis: ac loss $q_L(T)*[I_c(T)/I_c(76\ K)]$ (mW/m)
x-axis: Current (A rms)

ac losses in 1m Cable sections

"two" phase

AC Losses (mW/m) vs RMS Cable Current (A)
- Single Phase
- Two Phase

Jeff Willis et al
LANL

- Measurements in cable calorimeter

- Two phase - measure non-energized HTS cable

- Initially done to understand loss mechanisms

- *Two phase* arrangements also showed increased losses

- Two phase losses even more significant in other test cables.

- No known mechanism for two phase losses

- May affect accuracy of *three* phase data also

Possible mechanism for Two Phase Loss

•Estimates showed that the energy involved in 2 phase losses ruled out an 'isolated strand' mechanism

•Suggestion: unbalanced emfs could drive significant transport currents.

•The combination of ac field and ac 'transport' current is known to have enhanced losses

•Low resistance end connections complete the circuit
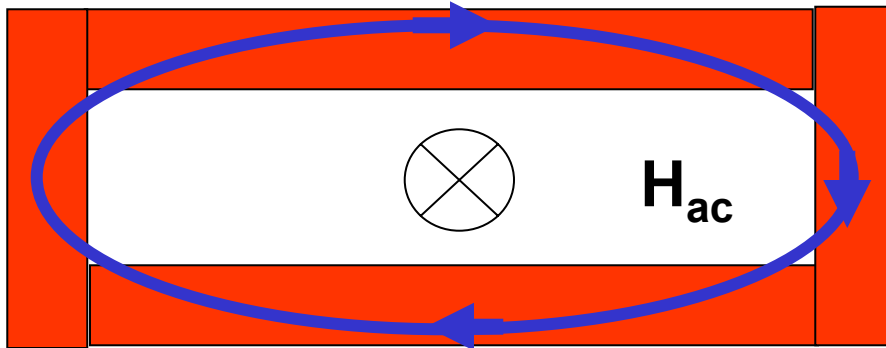

H_{ac}

Cu ends
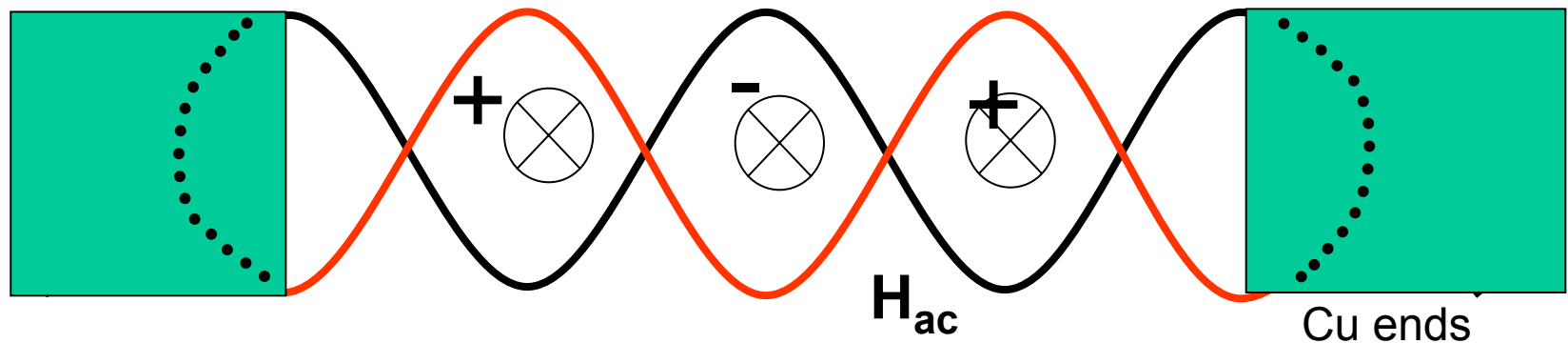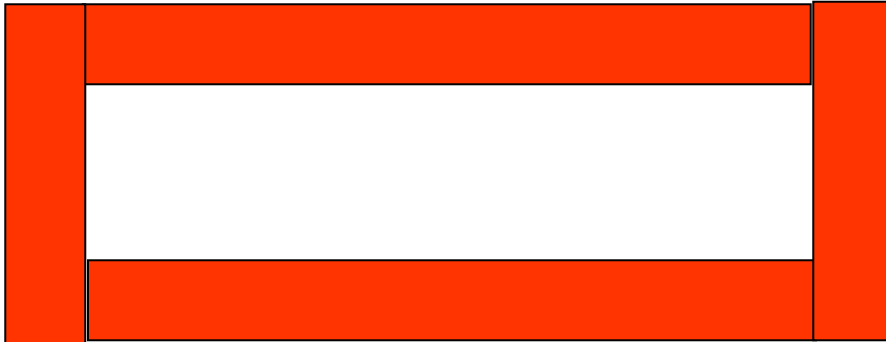
Test of Mechanism

Loop manufactured from BSCCO-2223 tape
Low resistance solder contacts

Test of Mechanism

Loop manufactured from BSCCO-2223 tape (AMSC)

Low resistance solder contacts

Apply perpendicular ac magnetic field
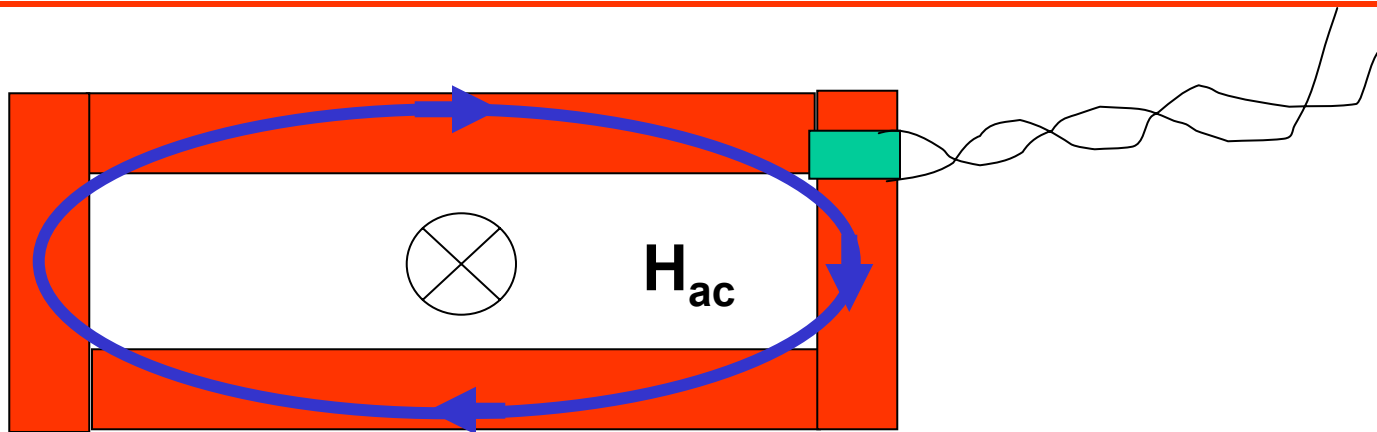
Generate emf - current flows

Current limited by impedance in loop

Contact resistance (low)
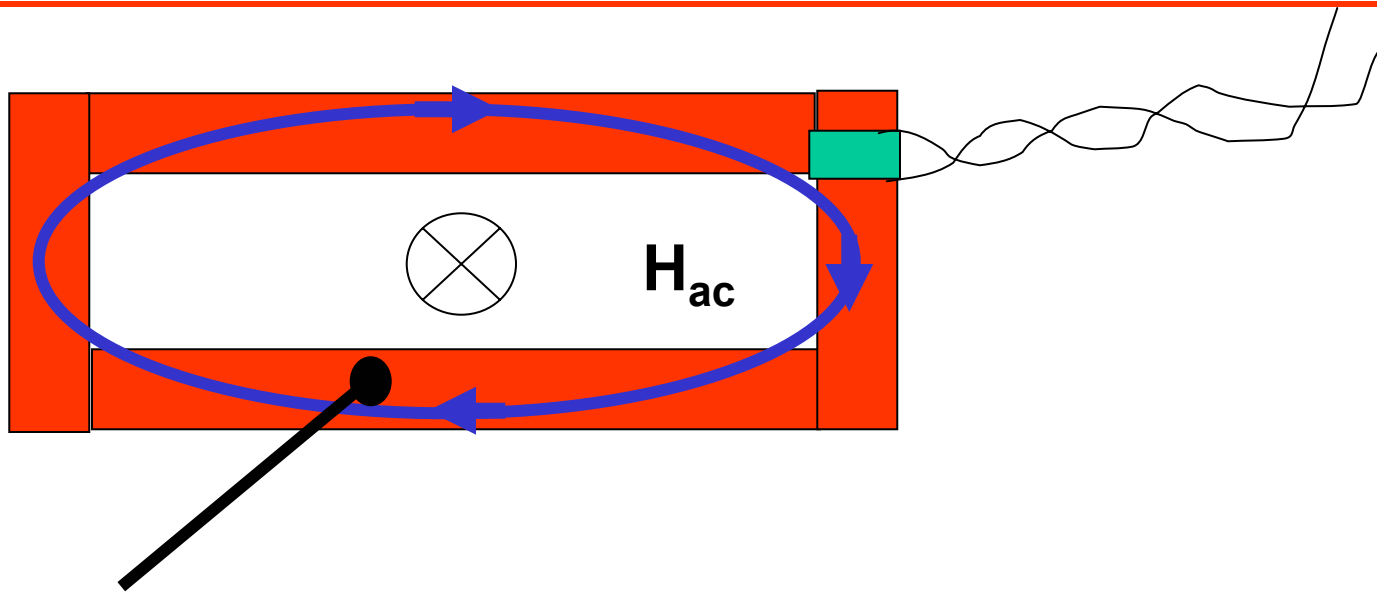
Ac loss derived voltage

Exceed I_C ?

Test of Mechanism

Shunt resistor (<1m.ohm) to measure current using lock in amplifier. Phase sensitive measurement
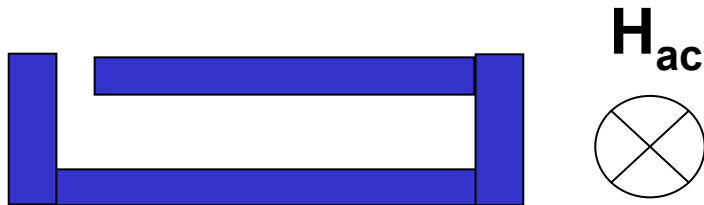
Test of Mechanism

H_{ac}

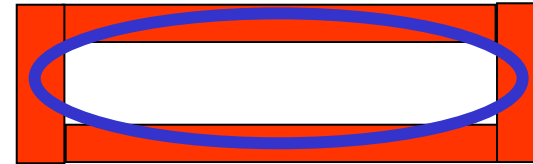Shunt resistor (<<1m.ohm) to measure current using lock in amplifier.
Phase sensitive measurement
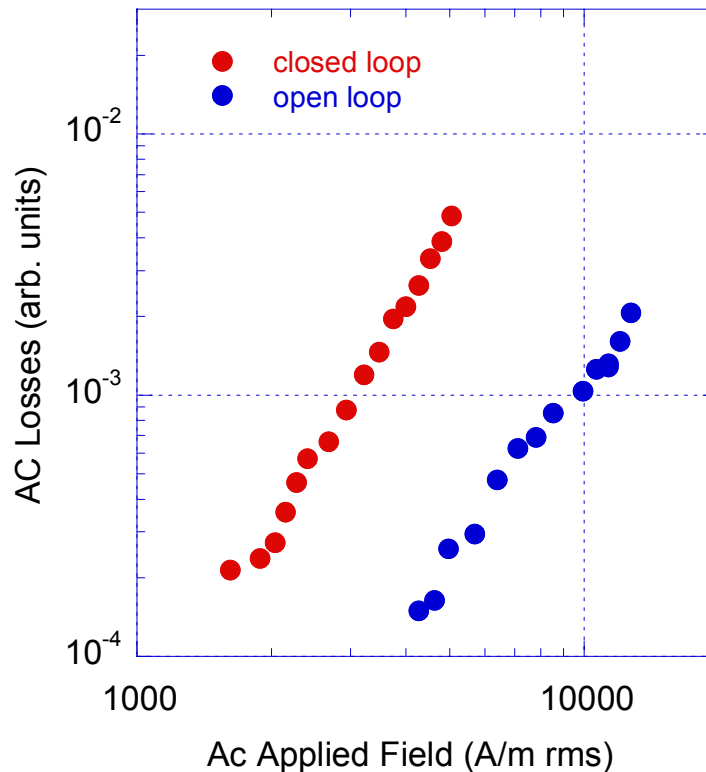Thermocouple to measure ac losses

Results: "open" and "closed" loop
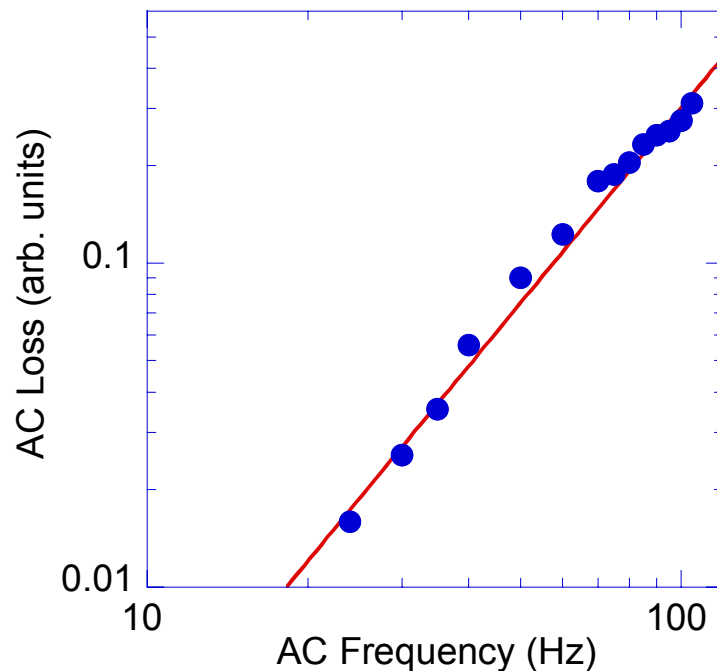

Magnetic ac losses

Magnetic and transport current losses

Losses in the closed loop are an order of magnitude higher than in 'open' loop ie without transport current
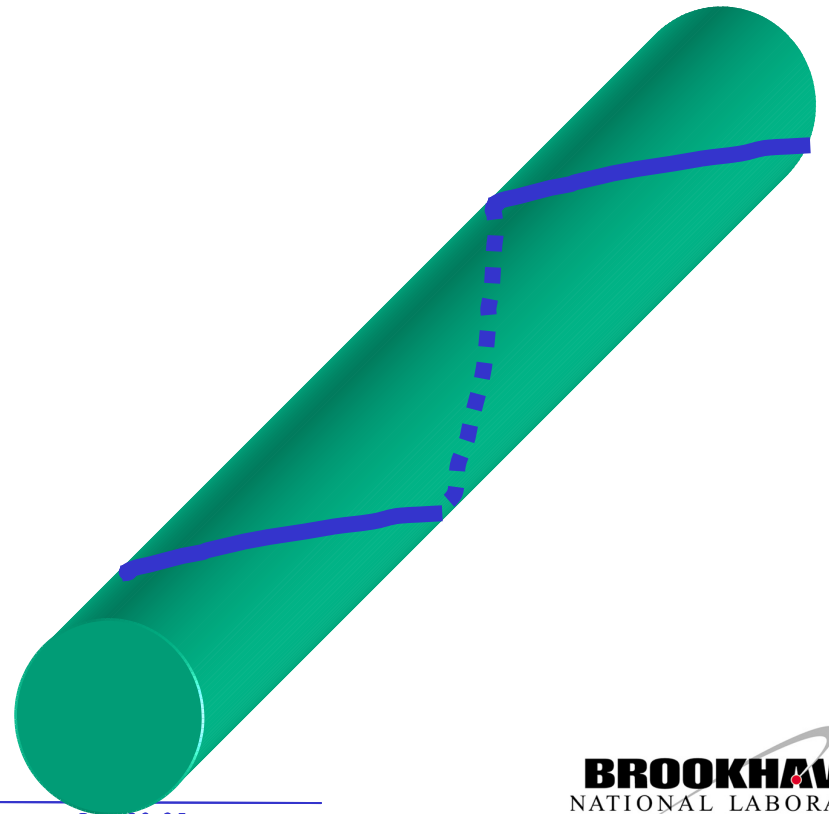
Results: Effect of AC Frequency

Losses vary as square of frequency at fixed amplitude

emf is proportional to frequency

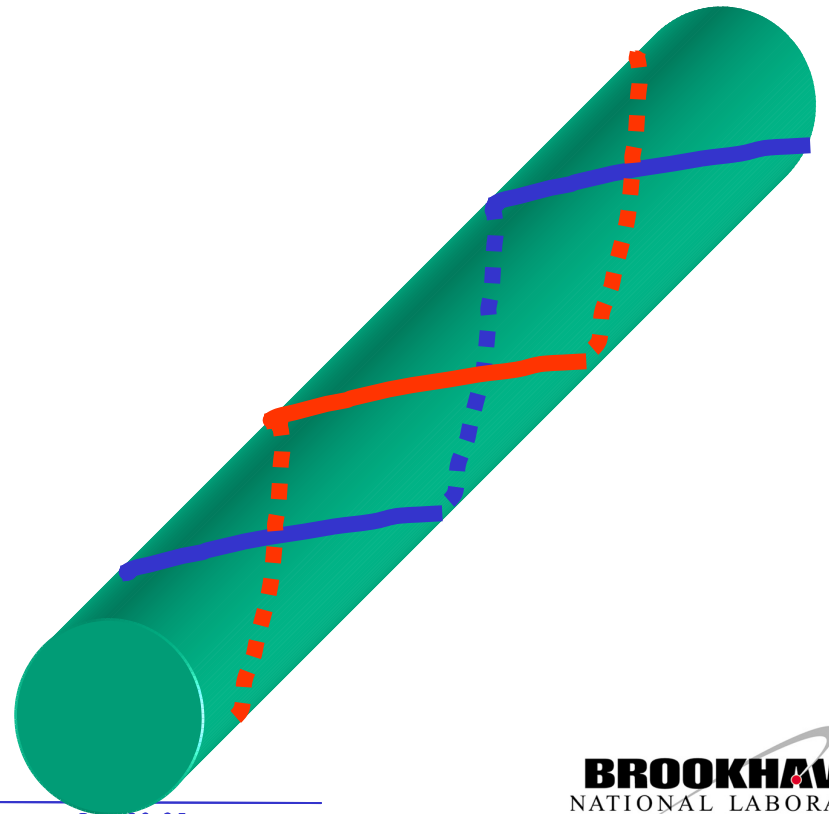Current proportional to emf (constant impedance)

"cable" test

- Construct 2 strand 1m cable, 25mm diameter (AMSC conductor as in cables)

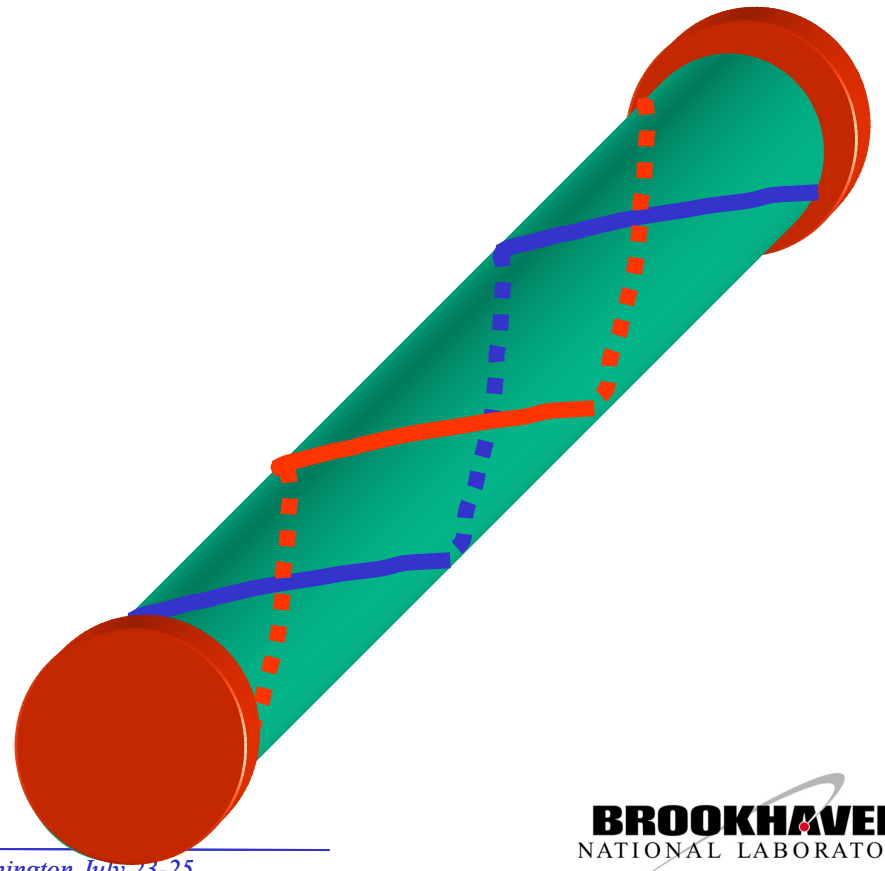# "cable" test

- Construct 2 strand 1m cable, 25mm diameter
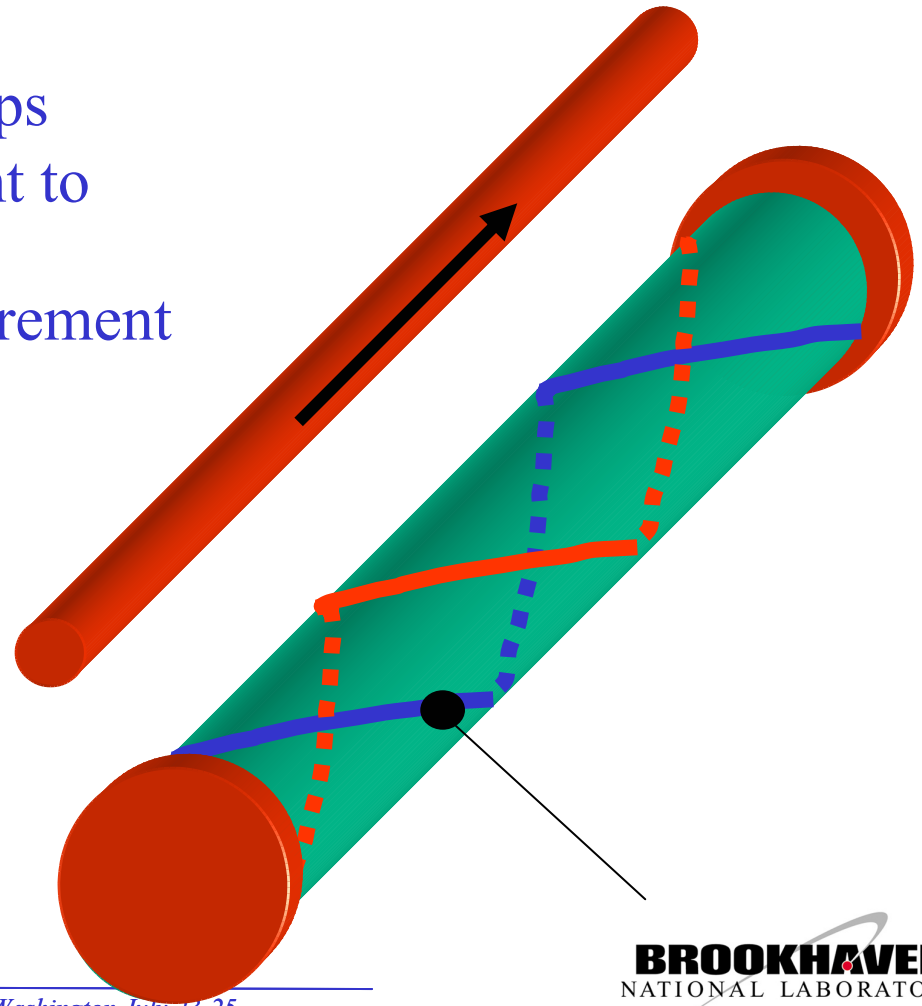- 1.5 turns each strand

"cable" test

- Construct 2 strand 1m cable, 25mm diameter
- 1.5 turns each strand
- Low resistance copper end caps

"cable" test

- Construct 2 strand 1m cable, 25mm diameter
- 1.5 turns each strand
- Low resistance copper end caps
- Copper rod carrying ac current to 5000A
- Thermocouple for loss measurement

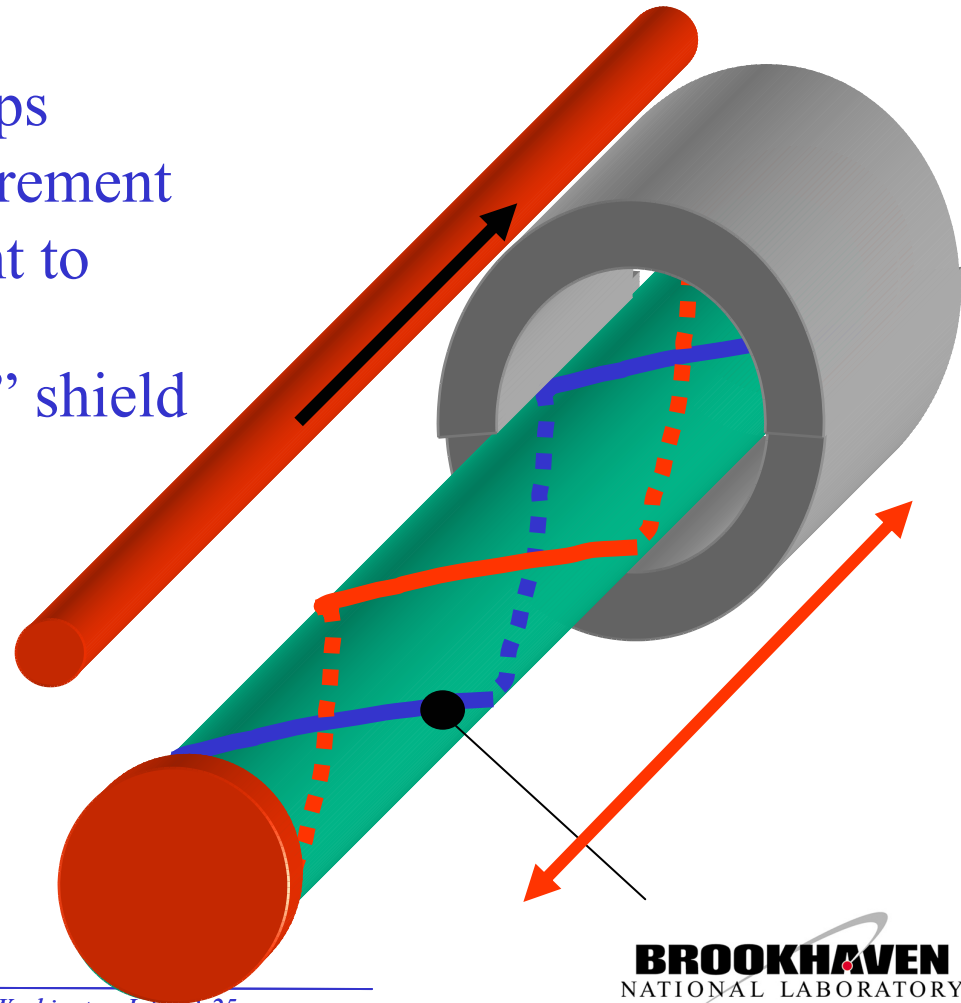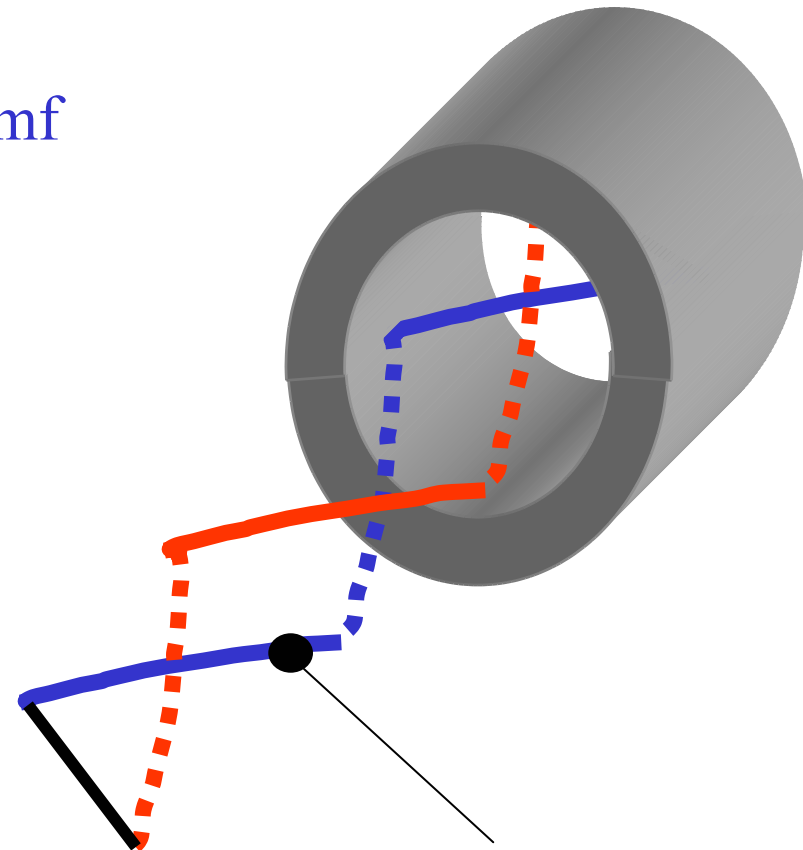# "cable" test

- Construct 2 strand 1m cable, 25mm diameter
- 1.5 turns each strand
- Low resistance copper end caps
- Thermocouple for loss measurement
- Copper rod carrying ac current to 5000A
- Sliding aluminum tube "eddy" shield

Results

- Losses change as eddy shield is moved
  - At 'zero' ½ pitch loop unbalanced
  - At 6inch should be no imbalance
- We can minimize 'unbalanced' emf
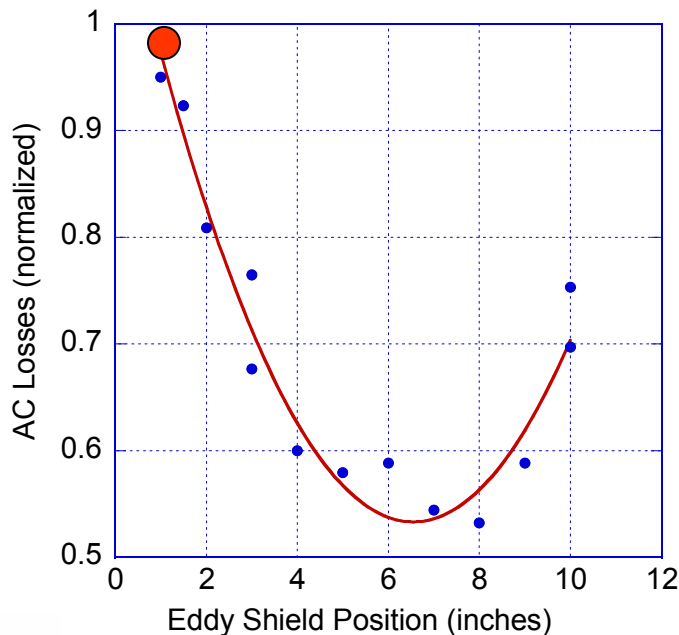
ac losses in BSCCO cables

Conclusions

☞ The mechanism of two phase losses is due to unbalanced emfs arising from a non-integer number of pitches in short test cables

☞An aluminum eddy shield can be used to minimize the effect

☞These losses are an artifact of short cables, but may affect cables up to 10's of meters scale

ac losses in YBCO (disc) films in perpendicular magnetic fields

in collaboration with:

ac measurements:

M. Iwakura, Kyushu Univ.

Theory:

J. Clem, Ames Lab., Iowa State Univ.;

T. Johansen and D. Shantsev, Univ. of Oslo

Specimens

F. Solovyov, BNL, S. Foltyn, LANL

Magneto-optical imaging

Q. Li, BNL

(a BES supported "Superconducting materials" program in Mat. Sci. Dept./BNL)

Why we need to study the losses in YBCO films in perpendicular ac magnetic fields?

Flux free region $B = 0$

Flux penetrated region: $J = J_c = $ const

Cylinder:

B_a

J J_c

B B_a

a R r

Thin disk:

B_a

J J_c

B B_a

a R r
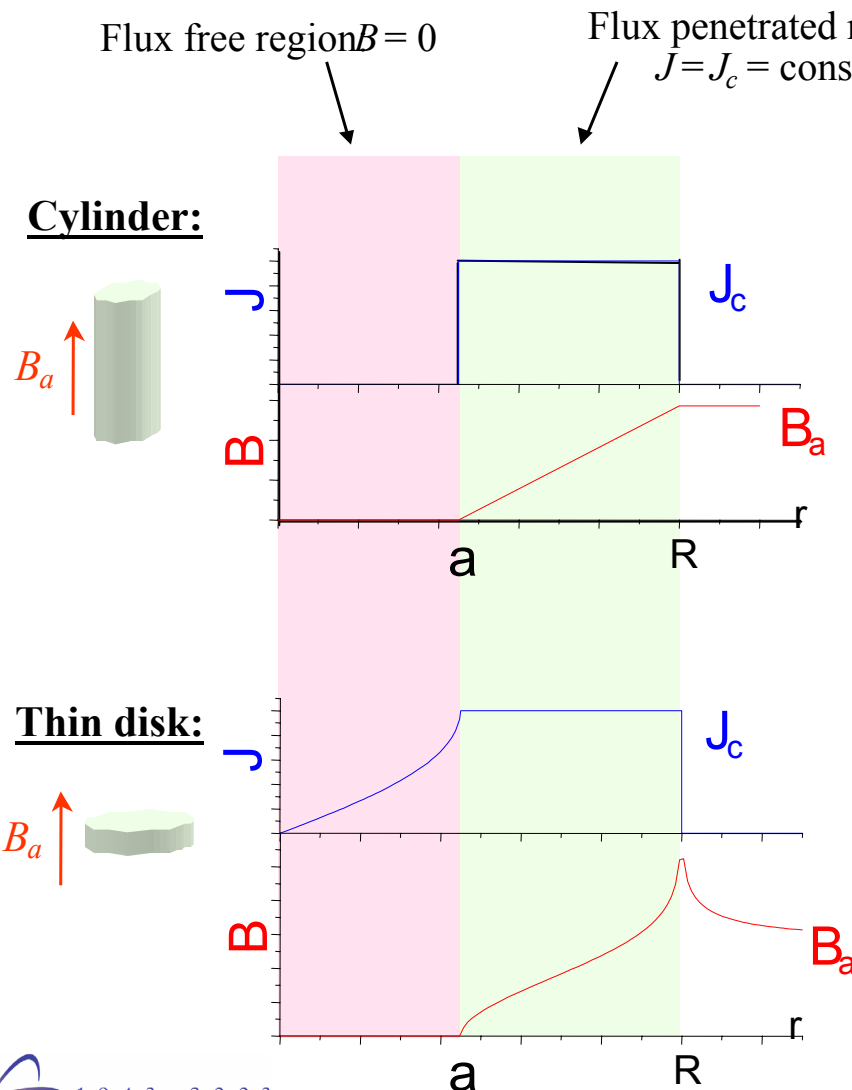
Cylinder (Bean Model)

$P \propto (1/J_c R) B_a^3$ below full penetration

Thin disk (Bean Model)

$P \propto [(R/d^3 J_c^2] B_a^4$ below full penetration

$R = $ radius, $d = $ thickness

Why we need to study the losses in YBCO films in perpendicular ac magnetic fields?
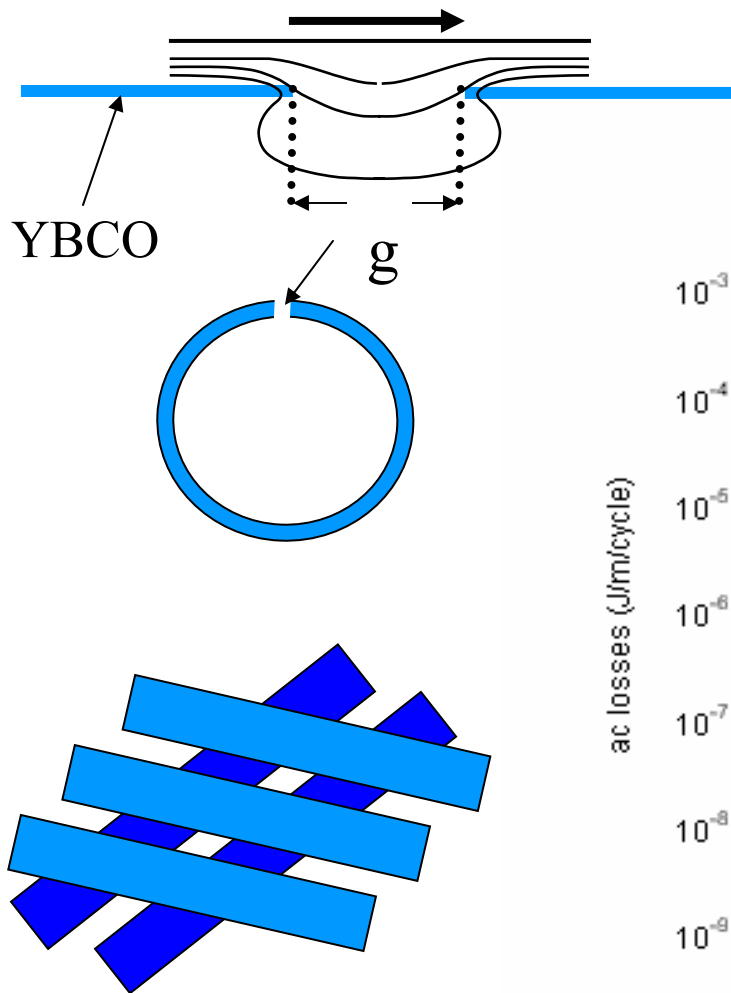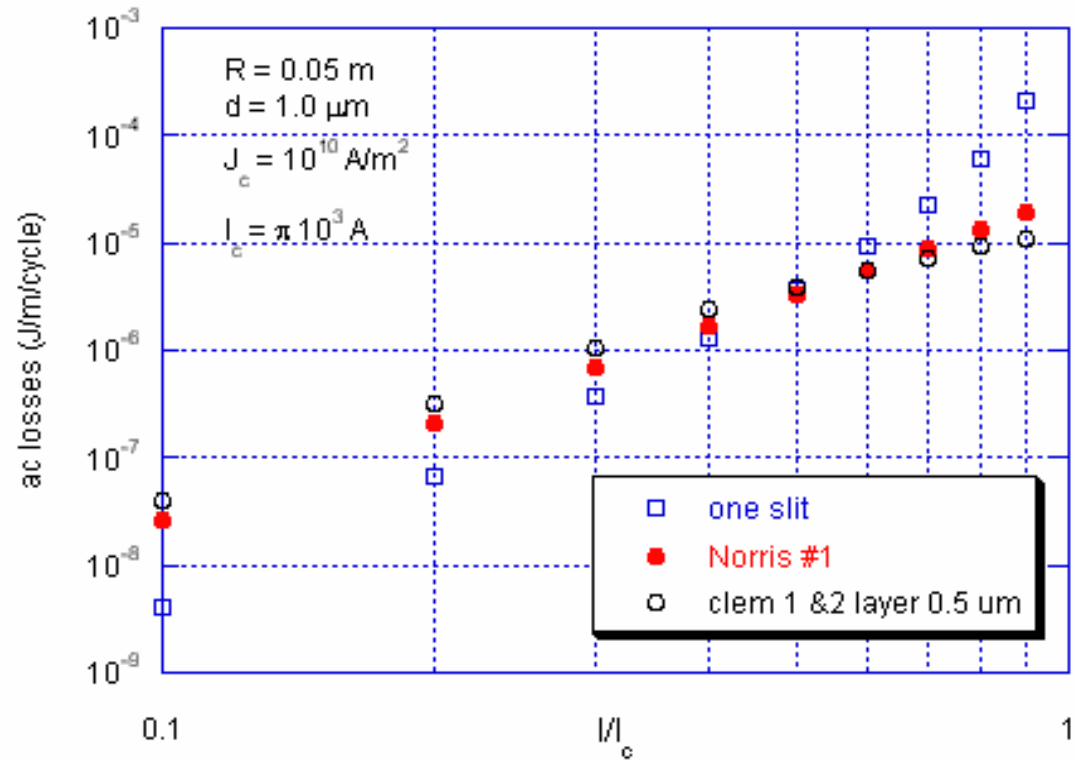

YBCO

g

$$\text{ac losses} = \mu_0 d^2 J_c^2 g^2/\pi \ f(I/I_c) \qquad \text{Norris / Majoris}$$

ac losses cylindrical shell w/ and w/o a slit

R = 0.05 m
d = 1.0 μm
$J_c = 10^{10}$ A/m^2
$I_c = \pi \, 10^3$ A

ac losses (J/m/cycle)

I/I$_c$

- □ one slit
- ● Norris #1
- ○ clem 1 &2 layer 0.5 um

$H_\perp$

ac losses in YBCO (disc) films in perpendicular magnetic fields

- Test of the theories on ac losses and determine how defects affect ac losses.

- Materials - YBCO films on STO: BaF_2(BNL), PLD(LANL)

- ac loss measurements:
  - susceptibility method (Kyushu Univ.)
  - in-plane pick-coil method (J. Clem) In progress.

- Other characterization methods:
  - magneto-optical imaging
  - dc magnetization

- YBCO films/STO BaF_2(BNL) PLD(LANL)
  - 1 μm thick films by BaF_2 process for the initial tests
  - 0.2, 1.0, and 3.0 μm thick films by PLD (S. Foltyn) to investigate thickness effects
  - diameter ≈ 5 mm

ac losses from YBCO (disc) films in perpendicular magnetic fields

Susceptibility

H_{ac}

In-plane coil

R_c
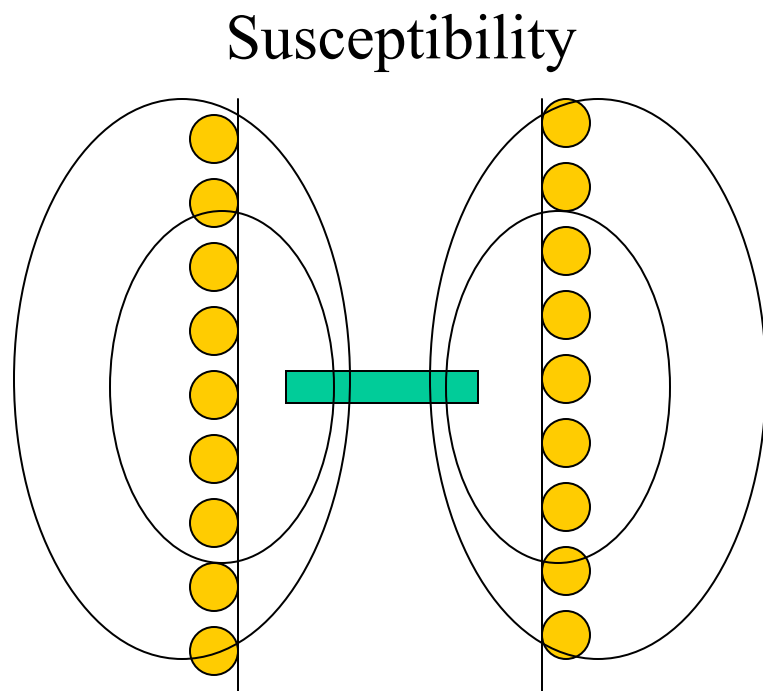
Requires calibration.
Iwakuma, Kyushu Univ.
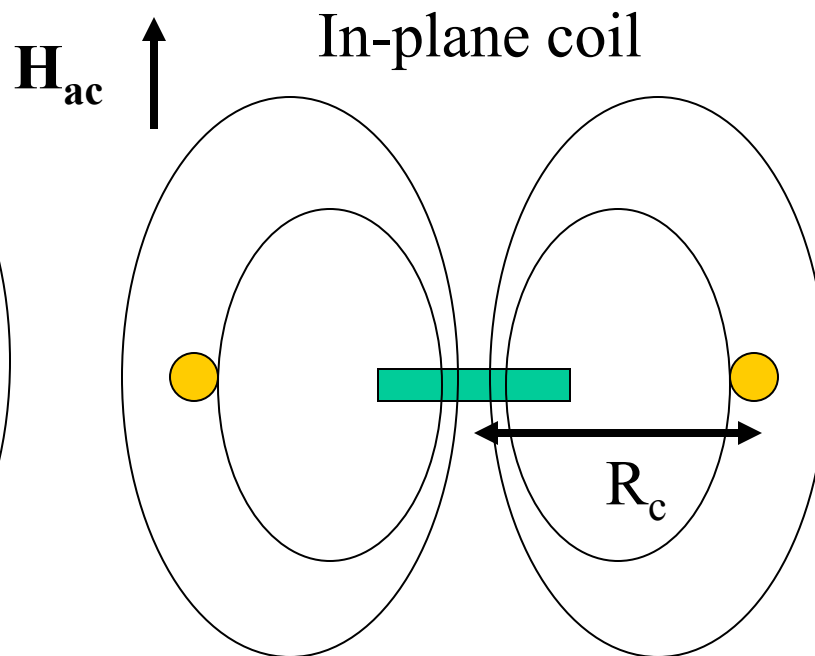
ac losses = $2R_c V_{rms} H_{a\ rms}$
John Clem

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ac losses from YBCO (disc) films in perpendicular magnetic fields

Magneto-optical Images from two YBCO disk films at 60 K (BaF2 process), 1mm thick; ~ 5 mm dia
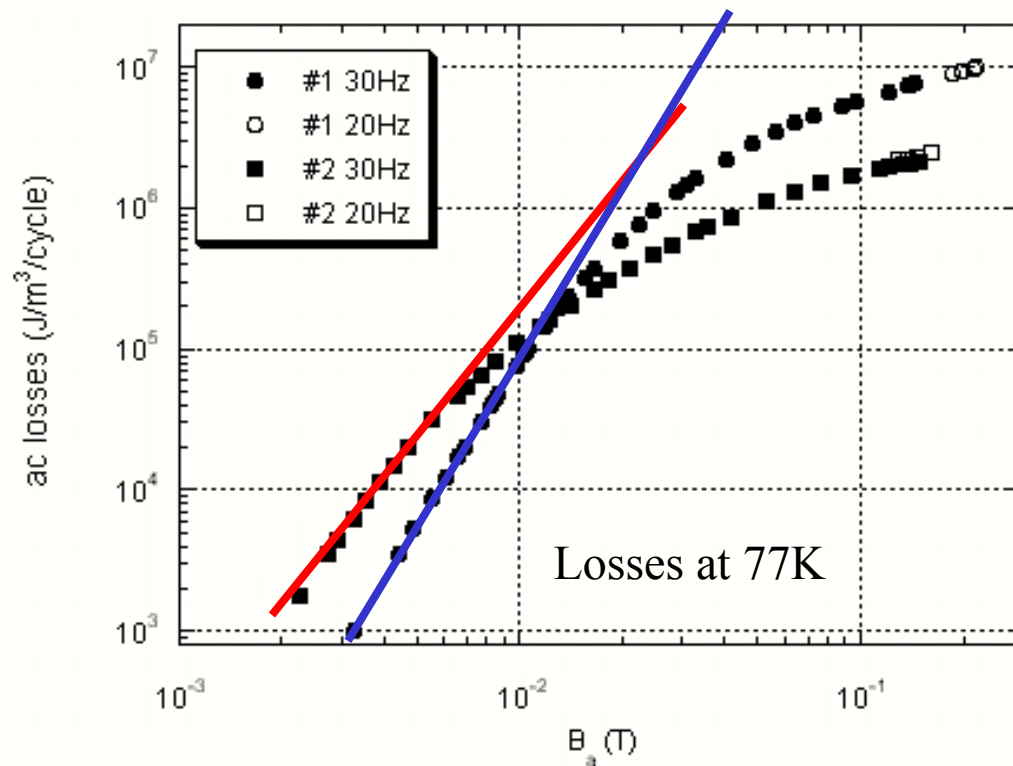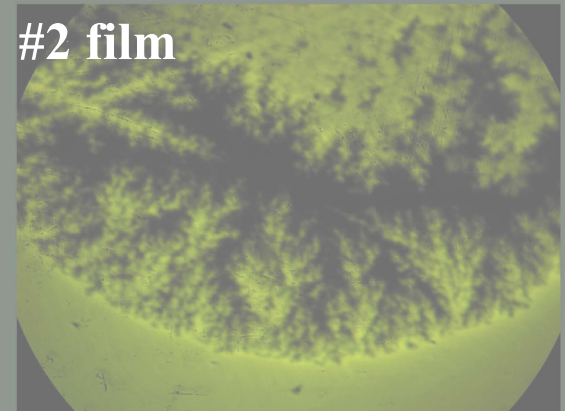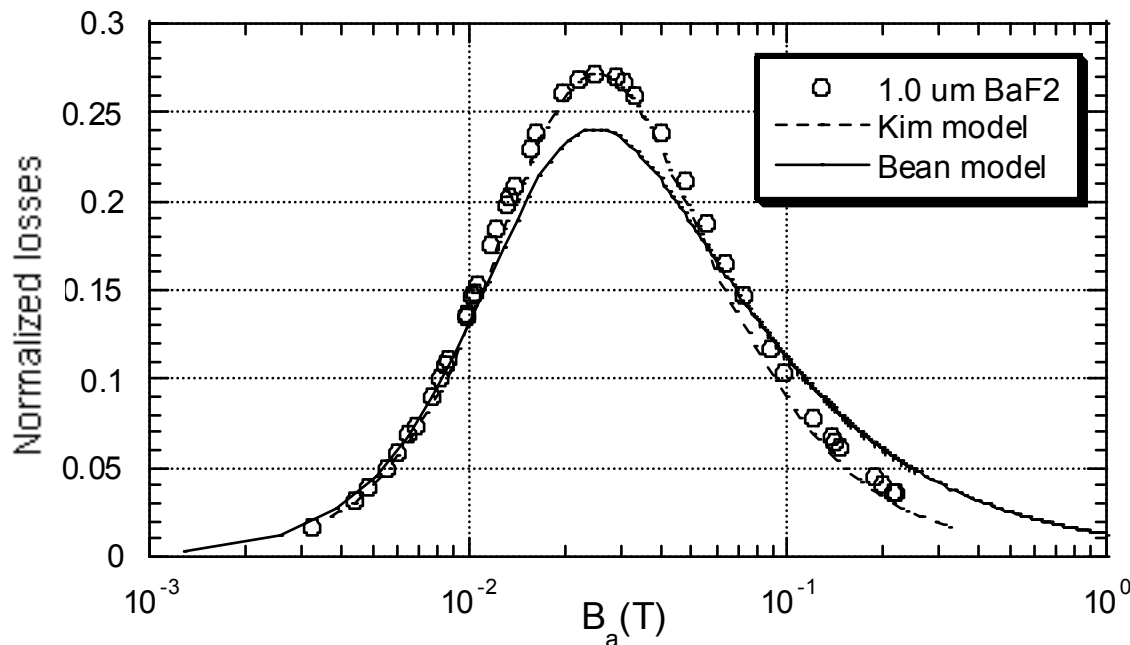

#1 film
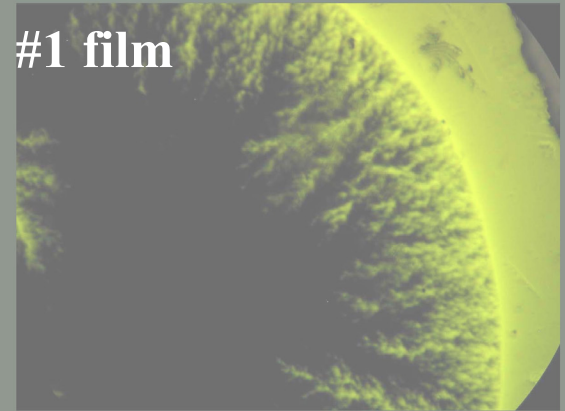
H = 300 Oe

#2 film

H = 300 Oe

Losses at 77K

Qiang Li and Z. Ye

ac losses in YBCO (disc) films in perpendicular magnetic fields

$$Q_N(B_a) = [\text{losses} /(\pi B_a^2/\mu_0)] (3\pi d/8R)$$

Theories:

Kim model:

D. V. Shantsev, et al., PRB **61**, 9699 (2000).

Bean model:

J. R. Clem and A. Sanchez, PRB **50**, 9355(1996).

$$J_c(B_a)=J_c(0)/(1+B_a/B_{0K})$$

ac losses in YBCO (disc) films in perpendicular magnetic fields

Some remarks:

1) ac loss theory based on the Bean J_c model is applicable at low fields, but need to use the Kim J_c model for high fields.

2) Macroscopically, not microscopically, uniform field penetration is important for comparing the measured ac losses with the theories.

3) If $Q_{N\,max}$ is less than 0.24, the film has significant defects.

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ac losses in YBCO (disc) films in perpendicular magnetic fields: Film thickness dependence

$$P \propto [R/(d^3 J_c^2)]\, B_a^4$$

YBCO films on STO by PLD (S. Foltyn/LANL):
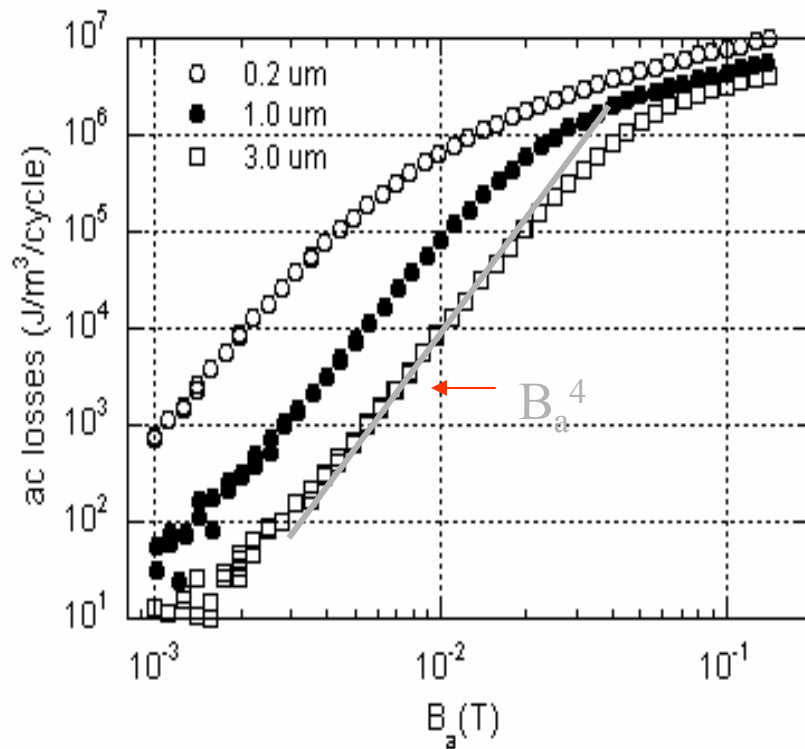
0.2, 1.0, and 3.0 µm thick

ac loss measurements at 77 K

dc magnetization

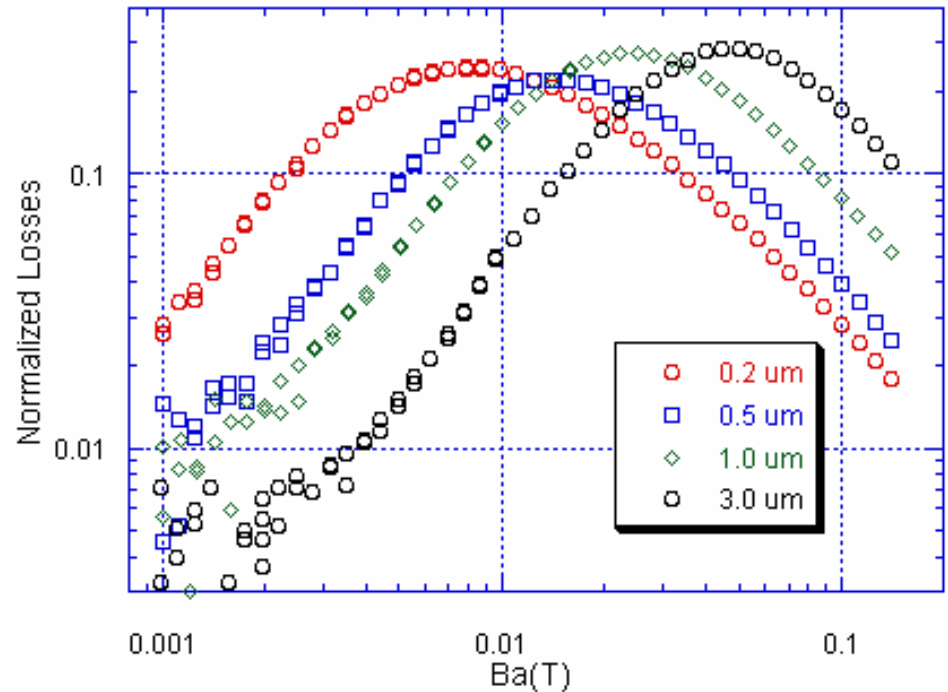dc self-field transport I_c (75 K)

magneto-optical imaging

ac losses in YBCO (disc) films in perpendicular magnetic fields: Film thickness dependence

$$P \propto (R/d^3 J_c^2) B_a^4$$
for $B_a \ll B_c = \mu_0 J_c d/2$

$$Q_N(B_a) = [\text{losses} /(\pi B_a^2/\mu_0)] (3\pi d/8R)$$

ac losses in YBCO (disc) films in perpendicular magnetic fields: Film thickness dependence
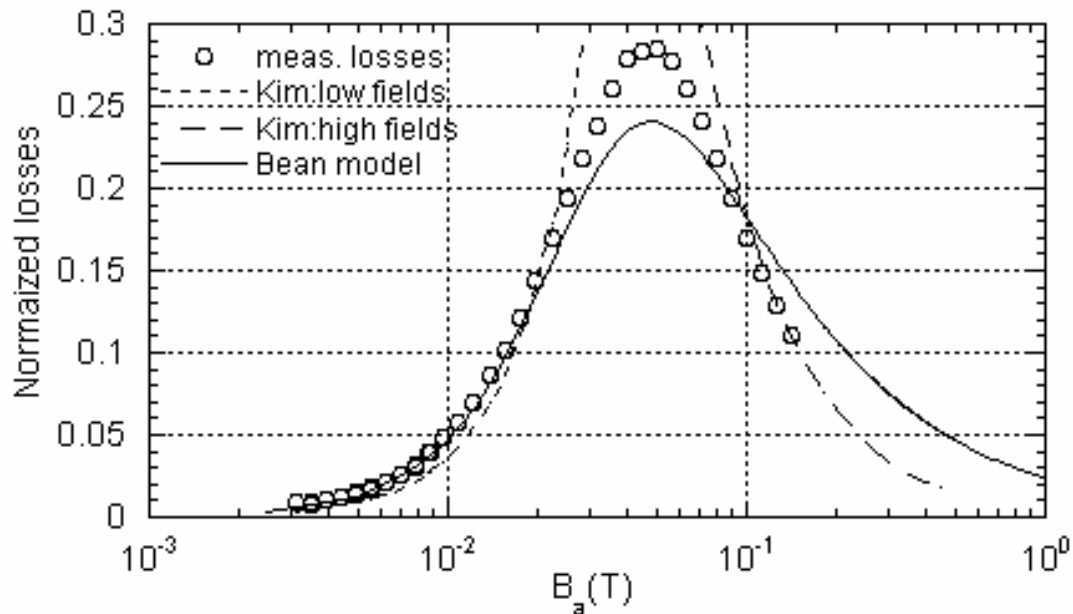
1. The behavior of the losses in all of the films were well described by the theories which included the field dependent Jc.

2. The thickness of the films is very important in determining the losses in perpendicular magnetic fields

3. *A puzzle:* ac and dc magnetization can be significantly different, particularly for very thin films. Hence, Jc(0) derived from dc measurements can not be used to calculate the losses in very thin films.

ac losses from YBCO (disc) films in perpendicular magnetic fields

Susceptibility

$\mathbf{H_{ac}}$

In-plane coil

R_c
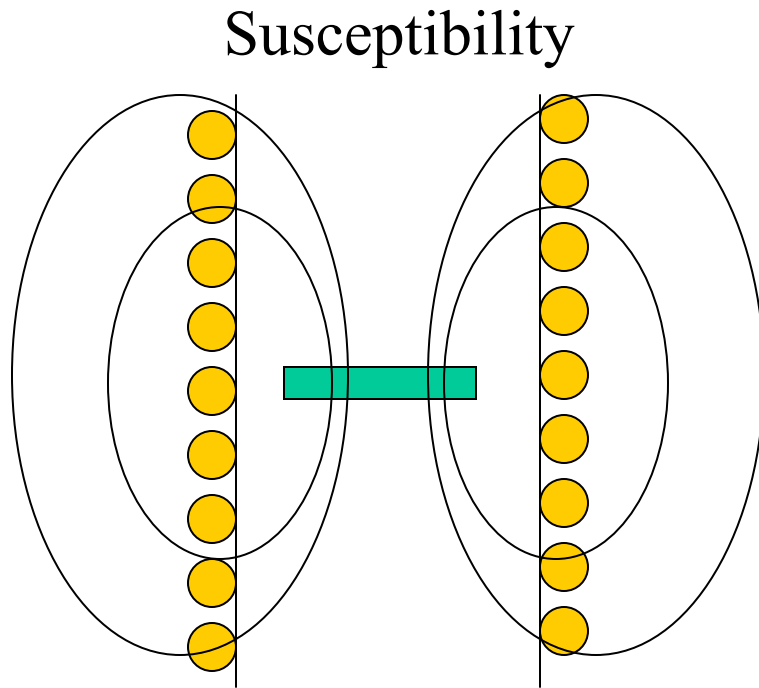
Requires calibration.
Iwakuma/Funaki
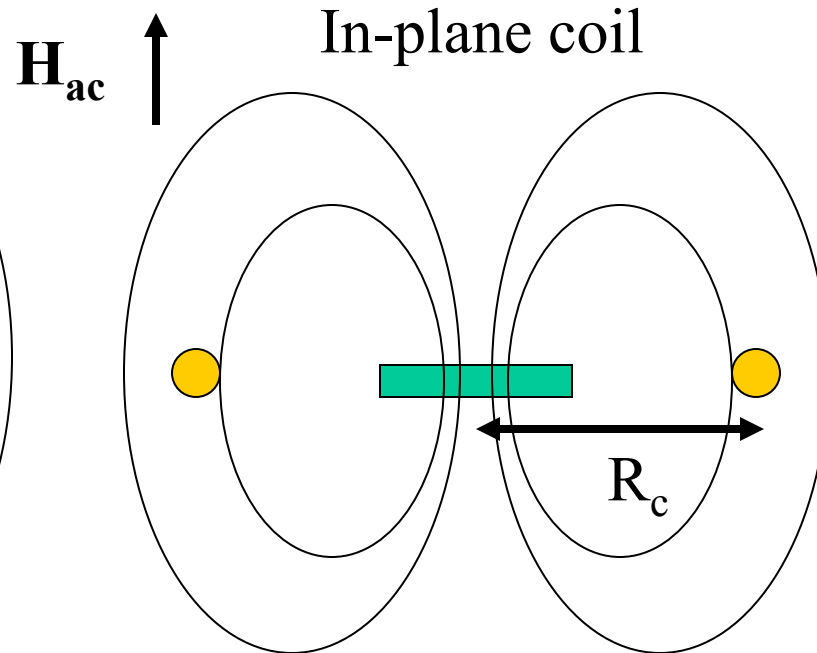
ac losses = $2R_c V_{rms} H_{a\ rms}$
John Clem

ac losses in YBCO (disc) films: In-plane coil method
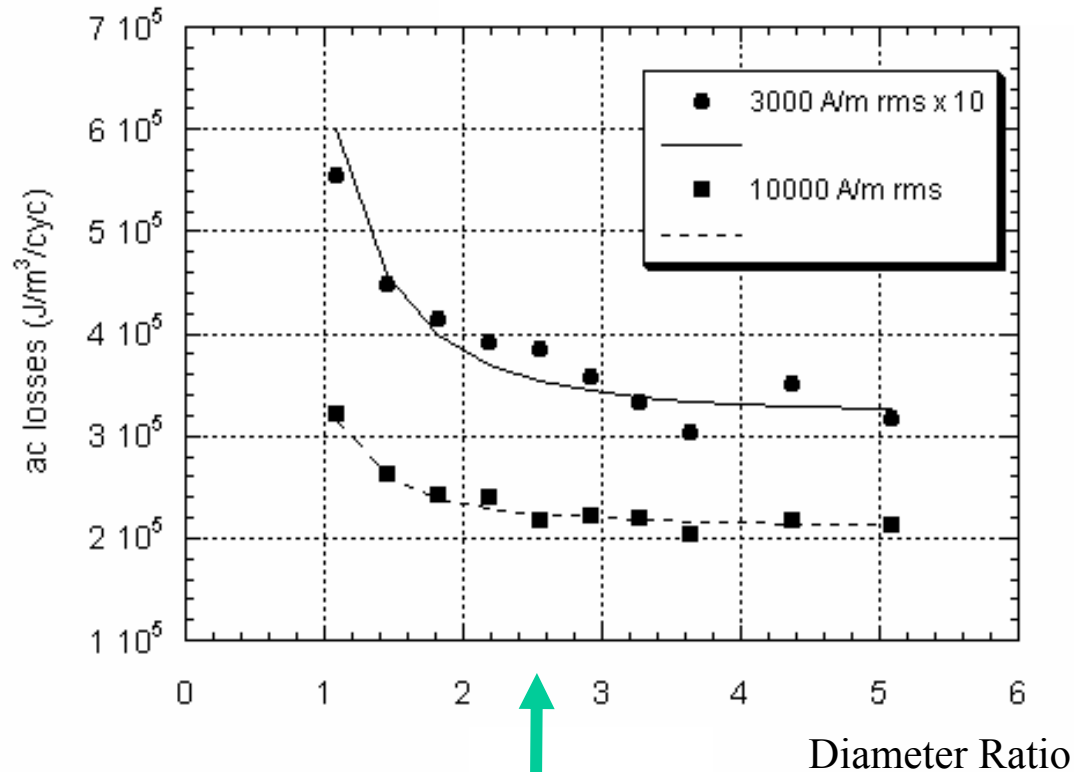
After damage

The diameter of the pick-up coil has to be more
than 2.5 - 3 times the diameter of the disk.

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RABiTS Coated conductor losses in perpendicular magnetic field

Linear at high fields

Cubic at low fields

- YBCO 150Hz
- YBCO 100Hz
- YBCO 50Hz
- YBCO 25Hz
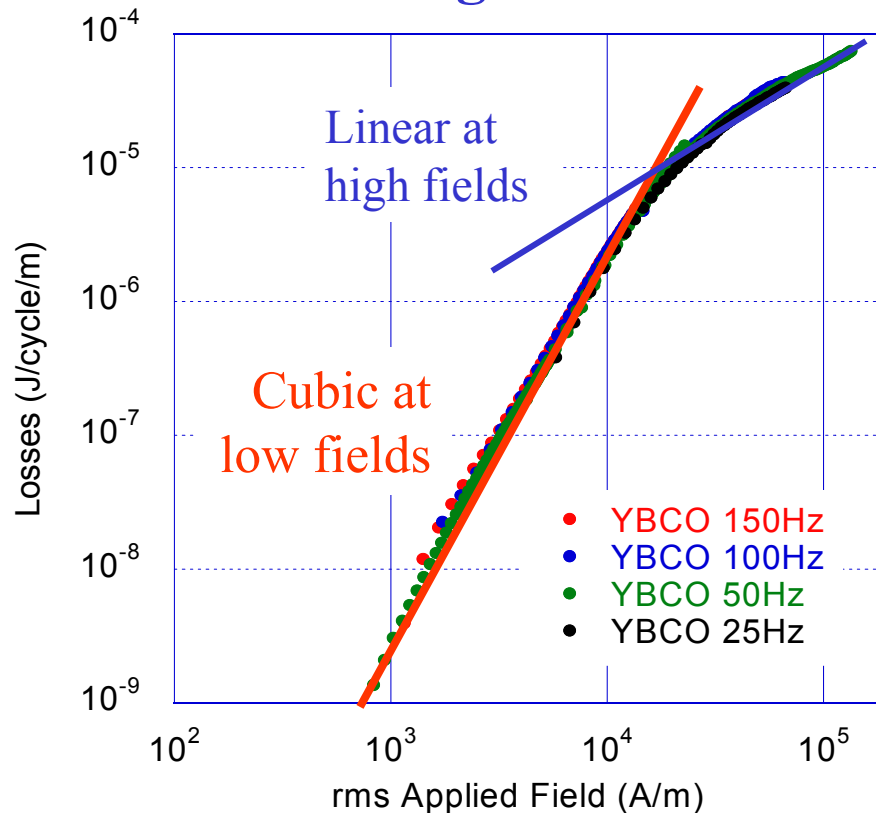
Materials supplied by AMSC

- Ic>100A
- 1cm wide
- Greater than expected from HTS theory alone
- Contribution of substrate (Ni/W plus Ni layer)??

RABiTS Coated conductor losses in perpendicular magnetic field

•Measure substrate alone in perpendicular orientation

•Not enough contribution from substrate
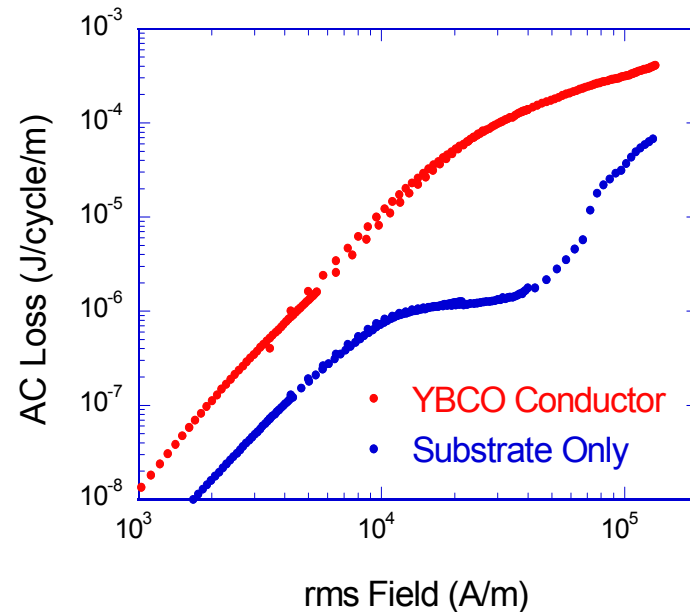
Look at Substrate Magnetic Properties

- Measure B-H curves for substrate
- Field parallel to face > material properties
- Obtain complex susceptibility
- Calculate volume losses as function of local field
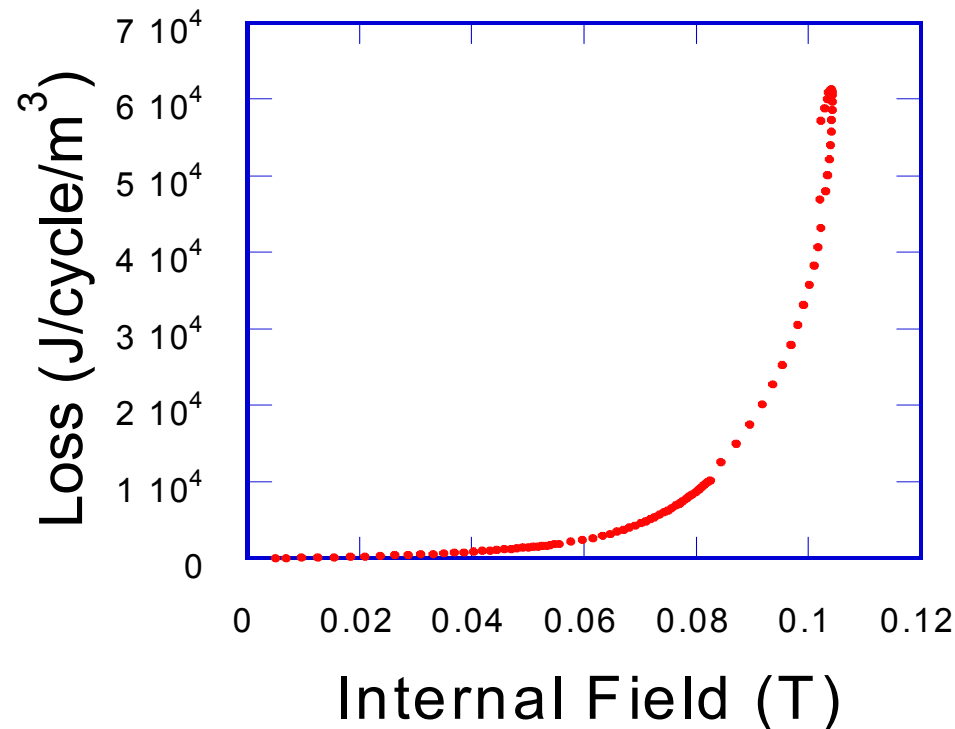
Look at Substrate Magnetic Properties

- FE calculation of 'local' magnetic fields

- Estimate local losses
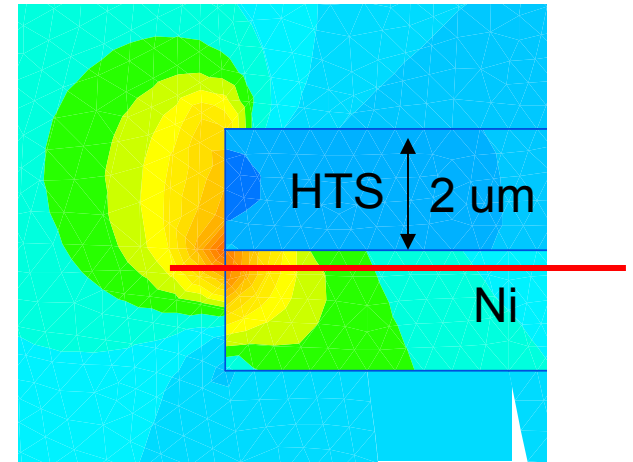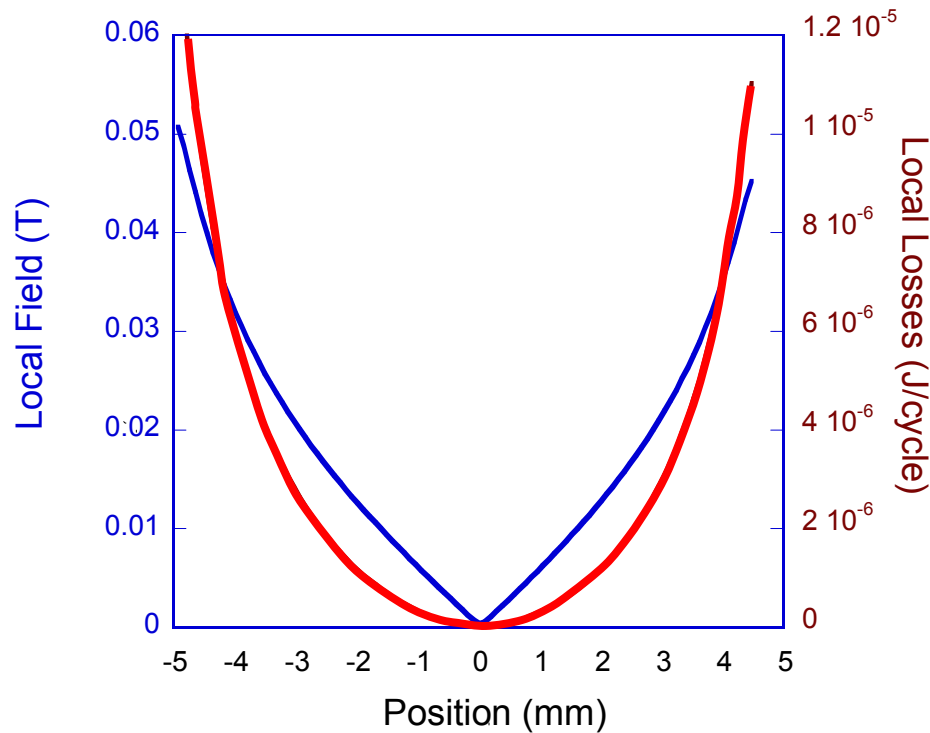
- Sum losses

- Gives reasonable agreement with data

- Losses are *localized* in substrate

Losses calculated in 0.1mm wide 'strips'

How to reduce magnetic losses?

- Double amount of HTS
- But change local fields
- HTS on outside
  - Shields Ni from magnetic field
- Significant reduction in losses
- Simulate double sided tape
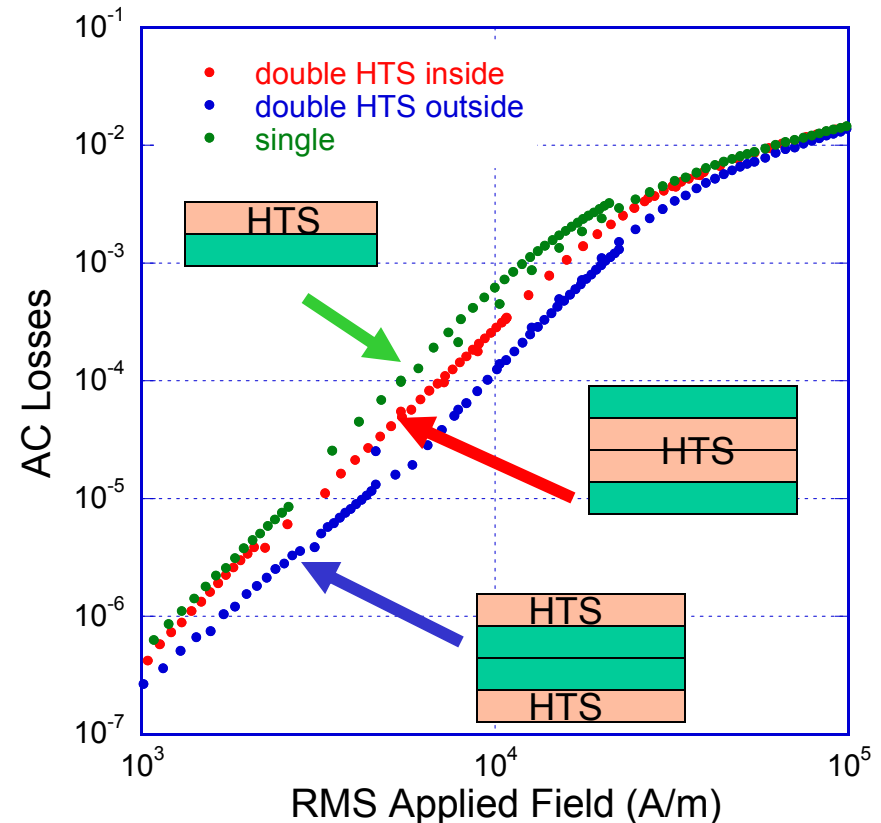
Losses due to combined ac transport currents and perpendicular magnetic fields

- AMSC material

- Calorimetric measurement

- Field and current in phase

- Low field
    - Transport losses dominate

- Higher field
    - Magnetic losses dominate

- Behavior similar to BSCCO and IBAD YBCO
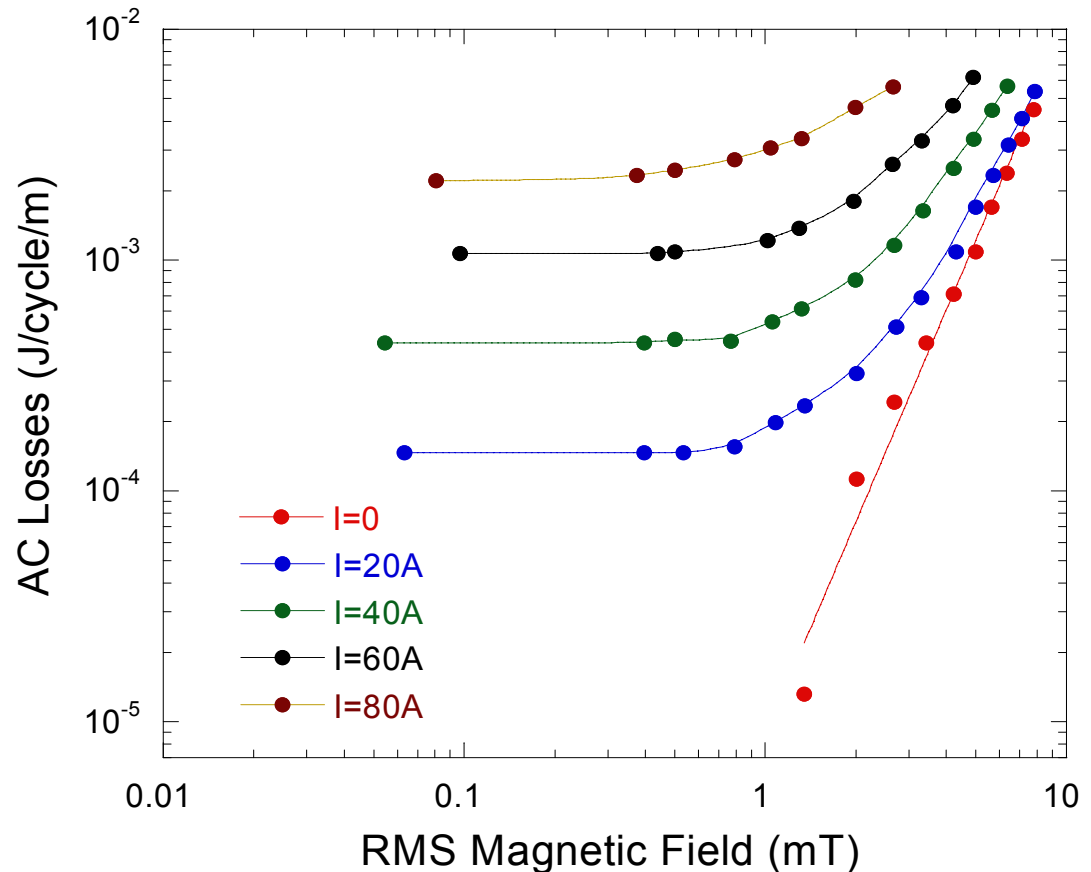
Changing Phase Difference between current and field?

- At Phase=0
  - Peak magnetic fields are
    - highest on one side of tape
    - Lowest on other side
- At phase = 90°
  - Peak fields are at minimum
  - Losses reduced
- Similar behavior to IBAD and BSCCO

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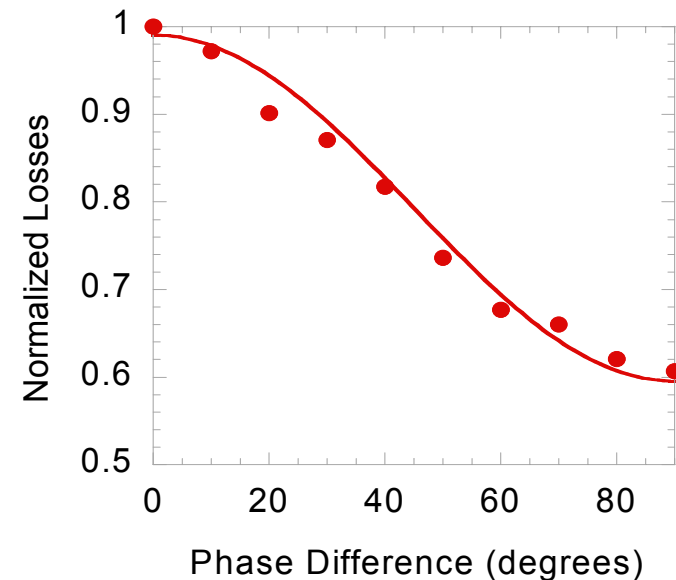
Losses in IBAD Tapes

- Material supplied by LANL Research Park Team
- IBAD MgO, 1cm wide
- Ic>100A
- Report losses due to perpendicular magnetic fields

- Hysteretic
- Three regions, different power laws

- Cubic ("ellipse") at low fields
- Not 'strip' power 4 at in any region
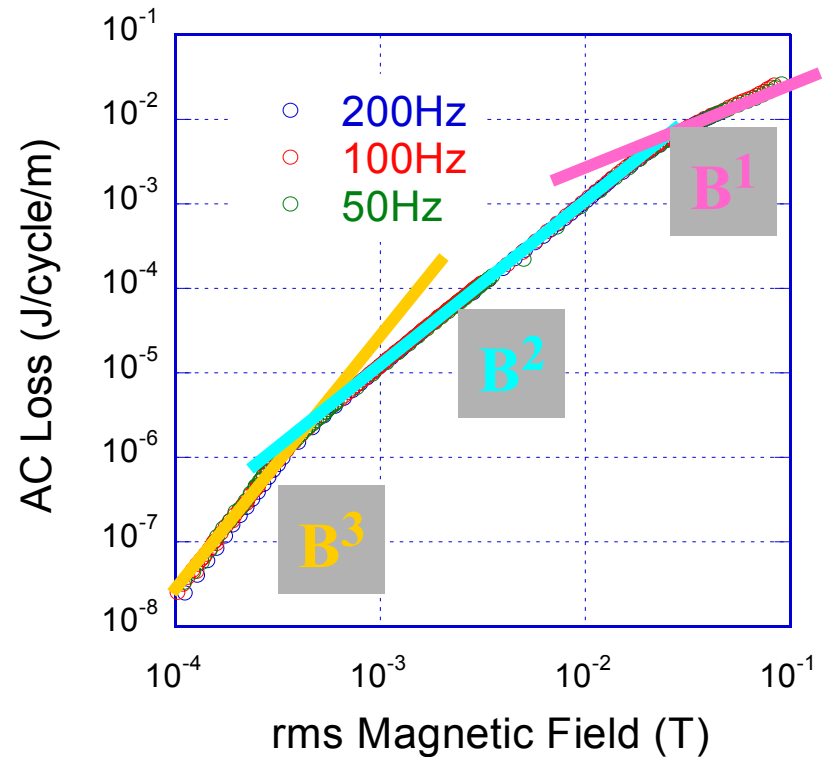
Reduce loss in IBAD Tapes

1cm wide single conductor

- Start with single conductor

- "Multi-filament" tape
  - Cut striations in HTS coating, produce
    - 5, 2mm wide with approx 50um gaps
    - 10, 1mm wide with appro 50um gap

- Losses reduce, character remains same

- No model as yet

Legend:
- ● 200Hz 10mm wide
- ● 50Hz 10mm wide
- ○ 200Hz 5 x 2mm wide
- ○ 50Hz 5 x 2mm wide
- ⊞ 50Hz 10 x 1mm wide

AC Losses (J/cycle/m) vs rms Magnetic Field (T)

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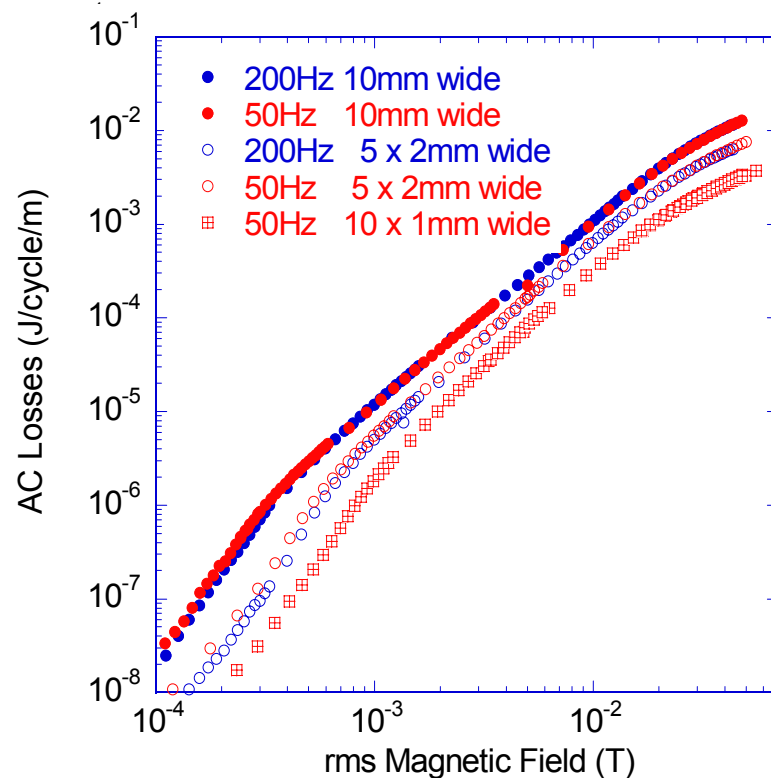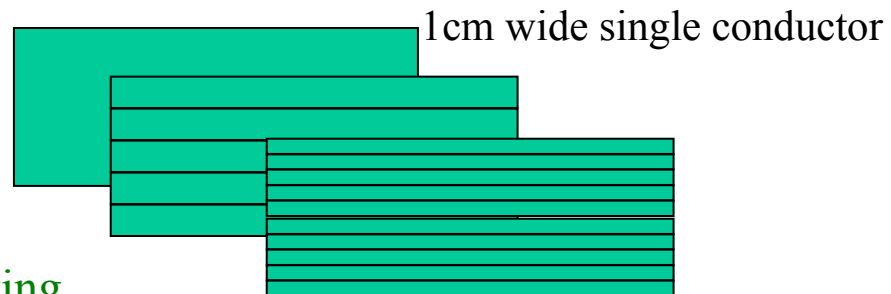
Project Plans and Objectives FY2003

This project aimed to study aspects of the ac losses of BSCCO tapes and YBCO coated conductors.

Specifically to

- Elucidate the mechanism for '2 phase' losses in BSCCO tape power cable short test sections

- Determine if this loss mechanism affected all loss measurements in short sections and if so how to minimize its impact.

- Test the applicability of theories for ac losses in YBCO coated conductors in perpendicular fields.

- Carry out measurements on coated conductor from various sources in ac fields and carrying ac transport currents.

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Project Performance FY2003

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Specifically to

✓ Elucidate the mechanism for '2 phase' losses in BSCCO tape power cable short test sections

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✓ Test the applicability of theories for ac losses in YBCO coated conductors in perpendicular fields.

✓ Carry out measurements on coated conductor from various sources in ac fields and carrying ac transport currents.

+ Initiated inter-lab (BNL, LANL, NREL) collaboration on cryo-stabilization of coated conductors.

Plans FY2004: BSCCO 2223

Significant application for **BSCCO 2223** tape will be 20- 40K range
Little ac loss data available in this regime

1. Measure ac losses in BSCCO 2223 tapes in the 20-40K temperature regime.
   - These measurements will for example cover losses in dc background fields plus ac ripple fields. These data are pertinent to a number of machine designs now underway.
2. Assemble predictive equations for the losses in this temperature range
   - Aid in machine design.
3. Determine conductor temperature rises when exposed to large fluctuations in applied field (ie 1T increase in 1second).
   - This is pertinent to the fault behavior of the conductor.

Plans FY2004: YBCO Studies

4. Measure losses on various samples with ac transport currents and ac magnetic fields.

   - data generation for prospective design studies.

5. Magnetic ac loss measurements of YBCO films in perpendicular fields:

   - comparisons with theories to include the field dependencies of critical current densities.
   - simple coil surrounding the specimen with J. R. Clem.

6. Measure of losses with fields at various angles to the conductor

7. Study conductor interaction (stacks, arrays) on ac losses.

8. Develop lower loss conductors

9. Study cryo-stabilization of coated conductors under ac conditions

   - This will become increasingly important as the IC of the available conductor increases
   - Eddy current losses in Cu stabilizer.
   - Characterization of stabilizer Cu and ac stability tests.   (LANL,BNL, NREL,ORNL)
     - Cu electro-deposition by Rahgu Bhattacharya/NREL

Research Integration

- BSCCO
  - Ames BNL LANL AMSC (material)
  - GE (CRADA with LANL)
- YBCO

  ac measurements: LANL, BNL, Kyushu University

  Theory: Ames Lab., Iowa State University, University of Oslo

  Specimens: BNL, LANL (Research Park and Core Program), AMSC,

  Magneto-optical imaging: BNL

  Stabilization: BNL NREL LANL

  US-Japan Collaboration on AC Losses in HTS

  Air Force STTR (LANL)